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Mobile Phased Antenna Array @ 6 GHz with Digitally Tunable Capacitor Phase Shifters

Carla Di Paola[1], Samantha Caporal del Barrio[1,2], Shuai Zhang[1], Arthur S. Morris, III[2], Gert Frølund Pedersen[1]
[1]Department of Electronic Systems, Aalborg University, Denmark, {cdp, scdb, sz, gfp}@es.aau.dk
[2]WiSpry Inc., Irvine, CA, USA, art.morris@wispry.com

***Abstract*—This paper evaluates the performance of the digitally tunable capacitor phase shifter, mounted on a phased antenna array, in the frequency range from 5 to 6 GHz. It is based on the WS1042, a single-chip, fully-integrated tunable RF capacitor featuring four high resolution, tunable MEMS capacitors under control of a MIPI RFFE serial interface. The design of the phased antenna array consists of four quarter wavelength dipoles printed on the short edge of an *FR4* substrate. Simulations including 70° and 105° phase shift demonstrated that the array can steer a beam wider than 80° and 100° respectively with a maximum gain of 7 dBi. The measurements, carried out in the MVG SG24, confirm that the prototype allows to reach the same scan angle observed in the simulations, but highlight a significant decrease in gain of 5 dB, due to the loss introduced by the four phase shifters and the port divider.**

***Index Terms*—Mobile terminal antenna, phased array, phase shifter, 6 GHz.**

I. Introduction

For the upcoming fifth generation mobile communication system (5G), the use of millimeter-wave (mm-wave) and centimeter-wave (cm-wave) frequencies, which satisfies higher data rate requirements [1]–[4], is limited by the free-space path loss, more significant than at the sub-6 GHz 4G bands. Therefore, directional phased array antennas turned out to be suitable also for the new generation mobile phones, due to their ability to exploit beamforming [5], in order to realize the desired coverage. In fact, steerable phased-array antennas are good candidates for mobile applications, thanks to their property to shape and adjust the radiation pattern electronically. The major drawbacks of phased array antennas are related to the phase shifters, responsible of the cost, compactness and power consumption of the entire structure. So, for the next generation phased antenna arrays, it is necessary to develop new strategies based on analog beam steering, as the one presented in [6], to replace the most common digital phase shifters.

The simplest beam-steering technique is frequency scanning [7], which consists on placing fixed-length delay lines between the radiating elements, so that a variation in frequency and consequently in wavelength, changes the relative phase of each element. In this case, though, the direction of the main beam depends on the frequency. The problem is addressed through the use of PIN diodes that switch between different lengths of delay lines or exploiting the phase-locked-loop phase shifters, proposed in [7], which offers the possibility to vary the phase shift with frequency.

The most popular digital phase shifters are diode phase shifters [8]–[10], characterized by fast switching time, low weight, low cost, but high insertion loss. [11] is an example of electrically steerable antenna using varactor diode based phase shifters. Implemented in the same metallic layer as the radiating elements, they allow to cover the range of ±32° with 11 dBi gain on average. Moreover, the phase shifters used in the design proposed in [12] implement inkjet-printed barium strontium titanate thick-films and are tuned by integrated metal-insulator-metal varactors. As in the previous case, they can steer the beam of ±30°.

On the other hand, the most known analogue phase shifters are ferrite phase shifters [13], [14], which are instead relatively bulky and heavy, and require significant switching power. They have the property to electronically steer the beam by providing signals of different phases to each radiating element. For example, the research effort in [15] leads to the design of a new ferrite phase shifter based on the use of three microstrip lines fed with phase differences, that allows reduction in cost, size and weight. A planar ferrite phase shifter with both analog and digital phase tuning is designed in [16]. Analog phase control is achieved by using an external magnetizing field and digital phase change is realized through p-i-n diodes that short the microstrip line with grounded copper strips having different phase properties.

However, at millimeter wave frequencies, the use of ferrite is limited by its material constraints. In [17] a planar magnetized semiconductor phase shifter is used to realize a tunable phase shift that overcomes the size, integration, and frequency limitations of the related ferrite device.

Another group of phase shifters includes the reconfigurable defected microstrip structure unit, proposed first in [18], which allows to achieve a phase shift of ±17° at 5.2 GHz. Despite the advantages in terms of cost, loss, fabrication process and integration with microstrip systems, it has a large electrical size, optimized then in the second version [19].

Finally, the 180° phase shifter in [20] is a novel design of microstrip-to-CPW-to-microstrip transition. Connected to the feedline of a double rhombus antenna, it employs via holes to transfer the current between the top and the bottom layers of the substrate and shows ultrawide bandwidth properties.

This paper presents a state of the art combination of beam steering antenna design and most agile phase tuning. It fills a gap to address performance at 6 GHz and introduces an innovative phase shifter, based on the digitally tunable capacitor WS1042, realized by WiSpry. Compared to the above mentioned phase shifters, the proposed device is more compact than [19], more robust than ferrite phase shifters, with the further advantage of requiring less switching power. The performance evaluation is conducted connecting the phase shifters to the phased antenna array proposed in [21]. Simulations prove that phase shifts of 70° and 105° between adjacent elements allow to steer the beam in the range of ±42° and ±55° respectively, with a maximum gain of 7 dBi. The measurements run over the whole structure corroborate the beam steering of 80° and 100°. However, the gain is reduced by 5 dB due to the loss introduced by each phase shifter and the port divider.

The paper is organized as follows. The design of the proposed phase shifters is presented in Section I. Section II describes the performance of the system in the simulated environment. Section III contains the results of the measured structure, followed by a comparison with the simulations. Finally, Section IV concludes the paper.

II. Phase Shifters Description

The WS1042 is an easy to use, flexible, single-chip, fully-integrated digitally tunable RF capacitor featuring four high resolution, tunable capacitors controlled by a MIPI RFFE serial interface. The two high linearity MEMS capacitor banks are digitally controllable between the values $C_{min} = 0.265$ pF and $C_{max} = 1.577$ pF and have factor $Q = 400$ at 1 GHz at C_{min}. Moreover, the internal design of the tunable capacitors guarantees continuous phase and amplitude during capacitance setting change. The WS1042 is packaged in a 2.2×2.6 mm ultra compact LGA type package and is based on the previous version, but it is configured to handle highest RF voltages with super fine capacitance step size. Target applications are tunable RF filter circuits and antenna aperture tuning. Due to a novel internal calibration module, part to part variation is reduced and the device results easy to use and program. The integrated DC/DC converter allows operation with one single VDD supply rail and, in addition to the RF ground pins, a digital ground pin, DIG GND, is introduced in order to isolate the DC/DC converter from the RF connections. Fig. 1 reports the WS1042 functional block diagram.

The design of the tested phased antenna array, presented in [21], consists of four quarter wavelength dipoles printed on the short edge of an FR4 substrate. The detailed structure is shown in Fig. 1 of [21].

III. Simulated Performance

As reported in Fig. 2 of [21], the working frequency of each dipole is in the interval from 6 to 6.5 GHz and the −10 dB return loss bandwidth is 500 MHz on average.

The phased antenna array has been simulated using CST Microwave Studio. The results prove that, using 70°, 0° and −70° phase shift between two consecutive elements, the array can steer a beam wider than 80°, from −42° to 40°, with a maximum gain of 7 dBi. In particular, the phase shift of 70° allows to scan the upper-left portion of the area. The

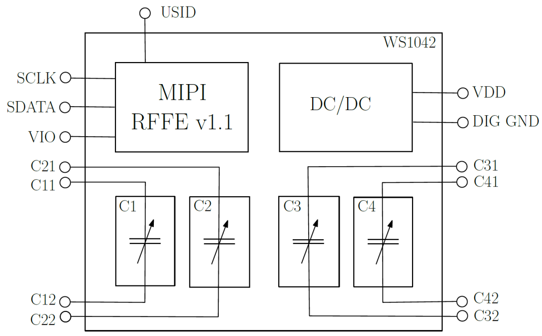


Fig. 1. WS1042 functional block diagram showing four tunable capacitors, RFFE interface and integrated DC/DC converter.

symmetric part is covered exploiting the opposite phase shift, −70°, whereas the absence of phase shift between the elements guides the beam towards the endfire direction. The radiation patterns in Fig. 2 show in detail the phased antenna array behavior.

Moreover, in the theoretical study, other values of phase shift are considered to improve the coverage. Simulations including 105°, 0° and −105° phase difference demonstrate that the system can steer up to 100° beamwidth, from −55° to 60°, with a gain of 6 dBi on average, as represented in Fig. 3

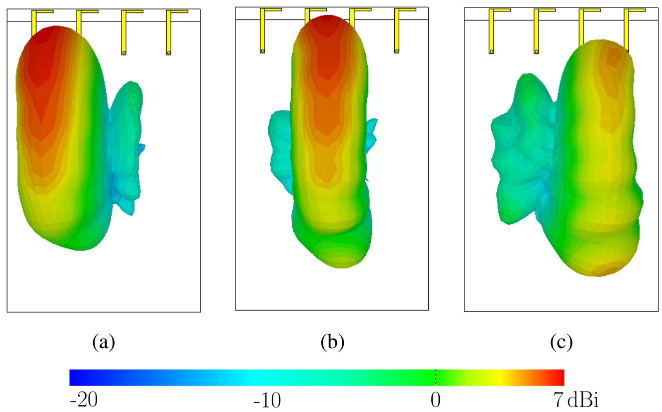


Fig. 2. Simulated radiation pattern of the phased antenna array, equipped with the WS1042 digitally tunable capacitor phase shifters, obtained with (a) 70°, (b) 0° and (c) −70° phase shift respectively [21].

IV. Measurements Results

The WS1042 digitally tunable capacitor prototype, realized by WiSpry, and the setup for the measurements in the MVG SG24, including the phased antenna array described in [21] and equipped with the phase shifters and a 1×4 splitter, are presented in Fig. 4(a) and Fig. 4(b) respectively.

The measuring equipment, located in the laboratory of the Antennas, Propagation and Millimeter-Wave Systems section at Aalborg University, consists of a ring with 23 bi-directional and dual polarized test probes and a computer receiving the measured data from the device under test.

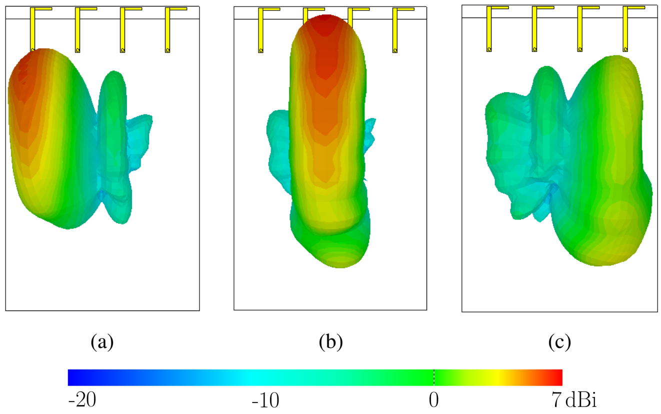
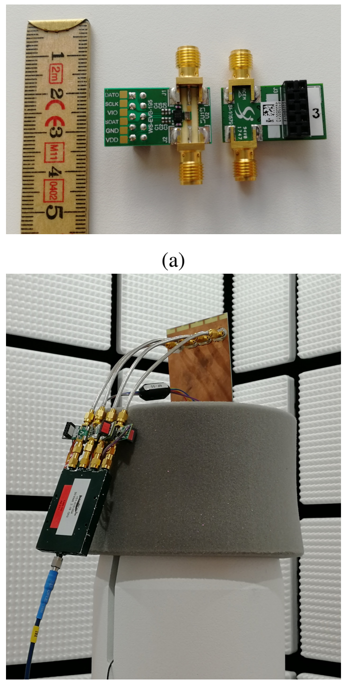


Fig. 3. Simulated radiation pattern of the phased antenna array, obtained with (a) 105°, (b) 0° and (c) −105° phase shift respectively [21].

The first step consists in measuring the configuration without phase shifters, to verify the results gathered from the simulations, i.e. radiation in the endfire direction with 6.9 dBi gain. The *E*-field radiated by the antenna system is evaluated over the 3D full sphere. The rotation of the setup, positioned in the center of the ring, allows to measure each point on the ϕ-axis, while the probe array carries out the measurement of each point over the θ-axis. The data are processed in *MATLAB* and reported in Fig. 5(b), in comparison with the ones of the simulated structure. A good agreement between the results is achieved in terms of the shape of the radiation pattern. As can therefore be inferred from the measured realized gain of 6.0 dBi, the splitter generates a loss of 1 dB.

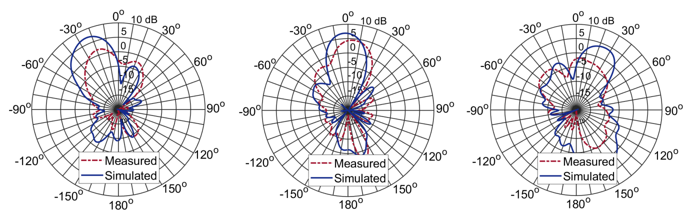
The following stage is based on tuning the four capacitors of each phase shifter, setting values in the interval from C_{min} to C_{max}, using the software SpryTune provided by WiSpry, ensuring that $C_1 = C_3$ and $C_2 = C_4$ (see Fig. 1), in order to maximize the efficiency. Since the range of phase shift achievable is 220°, from 80° to 180° and from −60° to −180°, it is impossible to test the second simulated case, with phase shifts of 105° and −105°. Regarding the configuration with 70° and −70° phase shifts, to obtain the desired angle, considering the values available in the range, the first phase shifter is programmed to have a phase of 80° ($C_1 = C_3 = C_{min} + 0.425$ pF and $C_2 = C_4 = C_{min} + 0.725$ pF), the second 150° ($C_1 = C_3 = C_{min} + 0.7$ pF and $C_2 = C_4 = C_{min} + 0.3$ pF), the third 220°($\equiv -140°$) ($C_1 = C_3 = C_{min} + 0.125$ pF and $C_2 = C_4 = C_{min} + 0.2$ pF) and the fourth 290°($\equiv -70°$) ($C_1 = C_3 = C_{min} + 0.025$ pF and $C_2 = C_4 = 0$). Other combinations of values of the capacitors allow to get the same phase, as illustrated in Fig. 6; for example, the symmetric setting $C_1 = C_2 = C_3 = C_4 = C_{min} + 0.725$ pF corresponds to 80° as well (Fig. 6(a)). The same procedure is followed in order to achieve −70° phase shift.

As is evident from all the various cases measured, the presence of the phase shifters does not alter the shape of the radiation pattern, but introduces a significant loss in gain of approximately 4 dB, 1 dB per phase shifter. In fact, looking at the radiation patterns plotted in Fig. 5(a), the simulated phased antenna array with 70° phase shift shows a maximum gain of 7.2 dBi, whereas the corresponding measured system reaches a gain of only 2.0 dBi. The extra loss of 1 dB is due to the splitter, as registered by the previous measurement. Same considerations apply to the results in Fig. 5(c), where the simulations report a realized gain of 4.8 dBi and the measurements an extremely low gain of −0.6 dBi.



(b)

Fig. 4. (a) WS1042 digitally tunable capacitor phace shifters and (b) measurements setup of the phased antenna array in the MVG SG24.



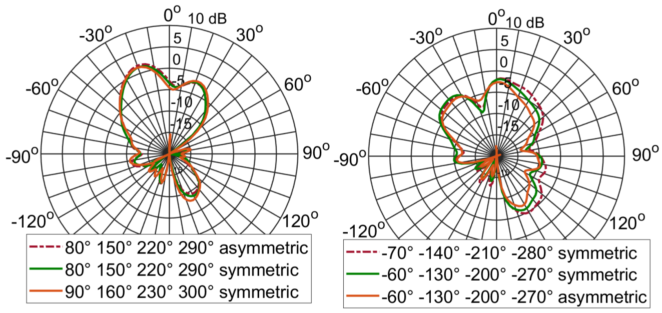
(a) (b) (c)

Fig. 5. Comparison between simulated and measured radiation pattern of the phased array antenna with (a) 70°, (b) 0° and (c) −70° phase shift respectively.

V. Conclusion

This work is focused on the analysis of the performance of a phased antenna array, equipped with the phase shifters based on the WS1042 digitally tunable capacitor.

The analysis of the phased antenna array, presented in [21], where the human impact on the radiation performance was investigated, is conducted through simulations using CST Microwave Studio and then measurements performed in the MVG SG24 in the frequency range from 5 to 6 GHz. Simulations considering 70° and 105° phase shift prove that the



(a) (b)

Fig. 6. Measured radiation patterns of the phased array antenna, obtained with different combinations of values of the capacitors giving (a) 70° and −70° phase shift.

array can cover more than 80° and 100° respectively with a maximum gain of 7 dBi. Moreover, the tuning of the phase shifters shows that different combinations of values given to the four capacitors allow to obtain the desired phase and, as expected, result in the same radiation pattern. The results of the measurements corroborate the simulation, as demonstrated by the comparison of the shape and scan angle of the radiated beams. Concerning the gain, a loss of 5 dB is observed. This is explained by the contribution of each phase shifter of 1 dB, since the configuration without them suffers a decrease in gain performance of only 1 dB, due to the splitter. Future study is aimed to improve the loss in the next generation tuners.

Acknowledgments

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